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Combustion of a Solid Cylinder in Low Speed Flows

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Introduction

Combustion of solids in low-speed forced flows at reduced gravity is relevant to fire safety in spacecraft (Friedman, 1988). Flame spread behavior at reduced gravity has been examined previously for thin fuels (Olson, 1988; Bhattacharjee, 1993; Grayson, 1994; Sacksteder, 1994). Combustion characteristics in low speed flow can be qualitatively different from those at higher speeds. In particular, flame extinction can occur at both high and low speed flows (Ferkul 1993).

For thick solids such as a solid cylinder, additional complications occur. It is known that two distinct flow regions exist when a cylinder is placed in a stream; a forward stagnation point and a wake (recirculating) region. The flame stabilization and extinction characteristics differ between these two regions (Spalding, 1953; Udelson, 1962). In addition, since the interior solid temperature continuously changes during burning, the percentage of gas-phase heat feedback into the solid affects the flammability characteristics.

This paper examines the combustion and extinction behavior of a solid PMMA cylinder in a low speed flow both theoretically and experimentally.

Mathematical Model

The mathematical model considers the flame to be a quasi-steady state gas phase phenomena. This assumption was based on an examination of the characteristic solid and gas phase time scales. The characteristic gas phase convection time for a cylinder with a 1.9 cm diameter (in a 10 cm/sec flow) was on the order of 0.2 seconds; the gas phase conduction time was on the order of 1 second. The characteristic solid phase conduction time was on the order of 350 seconds (McAdams, 1954). Thus, the solid heat-up process was much slower than the gas phase response time and a quasi-steady state gas phase was employed. The percentage of heat conducted into the solid (the ratio of the heat conducted into the solid to that from the gas phase) was treated as a parameter instead of solving the unsteady solid heat conduction equations. In a typical experiment, this ratio would be large immediately following ignition but would slowly decrease with time as the thermal profile penetrates into the solid interior.

The gas-phase model included quasi-steady, two dimensional continuity, full Navier-Stokes momentum, energy, and species equations with a one-step overall chemical reaction and with second-order, finite rate Arrhenius kinetics. On the fuel cylinder surface Arrhenius kinetics were adopted. The interface energy balance included heat conduction from the gas phase, surface radiative loss, latent heat of vaporization and heat conducted into the solid interior. Further assumptions were made: the flow was two dimensional and laminar, Prandtl and Lewis numbers were constants (0.7 & 1.0); body forces, gravity, and gas phase radiant heat transfer were neglected. The viscous dissipation and compressive work were neglected due to the low speed flow.

The system of equations was solved numerically. A modified version of the computer program written by Chen and Weng was used (Chen, 1990). Chen's work numerically simulated experiments conducted by Tsuji in which a counterflow diffusion flame was stabilized on the forward stagnation point of a porous cylinder (Tsuji, 1967). Two major steps were used in the numerical solution procedure: a domain-fitted grid system was generated (Thomas 1980), and then the governing equations were solved. With the grid fitting, the irregular physical domain was transformed into a rectangular domain. The transformed mathematical equations were solved by using Patankar's SIMPLE algorithm (Patankar, 1980). The properties used in the model computation were taken from (Foutch, 1987).

A parametric study was undertaken to determine the extinction boundary for this configuration by varying the ambient pressure, free stream velocity, and the percentage of heat conducted to the solid. In this report, only the effect of flow velocity and percentage of heat conducted to the solid are presented.

Numerical Results

The model was implemented for a 1.9 cm diameter PMMA cylinder burning in air. This study indicated that there were regions within the parameter space where there will be no flame. Flammable or non-flammable cases were determined by examining the reactivities within the domain. Visible flames were simulated by fuel reactivity contours (10^{-4} g/cm³ s) (Ferkul, 1993). Reactivity contours of the flame in 1 atm for varying amounts of free stream velocity and percentage of heat conducted to the solid are shown in Figures 1 and 2.

In Figure 1 the percentage of heat conducted to the solid was held constant at 30% and the free stream velocity

was varied from 0.8 cm/s to 150 cm/s. The flame was extinguished at the velocity extremes; the low speed case was quenched at 0.5 cm/s and at the high speed case was blown-off at 150 cm/s. When the free stream velocity was approximately 40-45 cm/s, local flame blow-off occurred at the forward stagnation point and the flame shape receded, changing from an envelope flame to a wake flame. (See Figures 1C and 1D.) In the wake flame cases, as the free stream velocity increased, the flame shrank but the maximum reactivity within the flame increased. When the free stream velocity was 150 cm/s the entire flame was extinguished. In envelope flame cases, as the free stream velocity decreased, the flame stand-off distance increased, and the flame tips became shorter, and weaker as measured by the flame reactivity. At a free stream velocity of 0.5 cm/sec the flame was extinguished.

To compare with previous studies of stagnation-point diffusion flames (Foutch, 1987) the stretch rate at the forward stagnation point is defined as $2U/R$ (U is the free stream velocity and R is the radius of the cylinder). The stretch rate for quenching and stagnation point blow-off for this sequence was about 1.1 - 1.7 1/s and 85 - 95 1/s respectively. Comparing these results to previously published results (T'ien, 1986), we find that the stretch rate limits were about 1 and 100 1/s, which provided reasonable agreement.

In Figure 2 the free stream velocity was 10 cm/s and the percentage of heat conducted to the solid was varied. As the percentage of heat conducted to the solid was increased, the flame became weaker; the flame decreased in length and the stand-off distance decreased. At low speeds, the flame shrank to the forward stagnation point before being extinguished. Extinction occurred when the percentage of heat conducted to the solid was greater than 55%.

Experimental Setup

Reduced-gravity experiments burning cast polymethyl methacrylate (PMMA) cylinders 1.9 cm in diameter were conducted. The cylinders had a length of 2.5 cm whose axis was perpendicular to the flow. Steel disks were placed at the end of the cylinders to prevent an end flame. The experiments were conducted in an apparatus equipped with a 23 liter combustion chamber and forced flows of 2 to 60 cm/sec (at 1 atmosphere). The flow was conditioned before entering the chamber to create a uniform flow in the test section, verified using flow visualization and a hot needle anemometer.

Multiple flow velocities were examined (8, 10, 12 and 13 cm/sec.) using air as the oxidizer at one atmosphere pressure. Flame images were recorded on video tape using two color ccd video cameras. A computer controlled the experiment and recorded sampled pressure, temperature and acceleration data. Combustion was initiated using a hot wire ignitor.

Low-gravity was obtained on board NASA's KC-135 research aircraft. In flight the airplane followed a Keplerian trajectory that produced 20 to 30 seconds of low gravity. (Lekan, 1992). Accelerations on the order of 0.01g's were measured during the low-g portion of the trajectory. The periods of low-g were preceded and followed by periods of high-g; 1.5 to 2 g's. Because the time needed to establish combustion took longer than the entire low-g period, the sample was ignited in the high-g portion of the trajectory.

Experimental Results

Once the sample was ignited, the flame propagated around the cylinder until it formed an envelope flame; the envelope flame took approximately 20 to 30 seconds to develop. Figure 3 shows a sequence of flame images for a case with a forced flow velocity of 10 cm/sec. Figure 3A shows the envelope flame at approximately 1g. In most cases the time from ignition till the entry into low-g was approximately 45 to 50 seconds. During the transition from high-g to reduced gravity the flame's plume shrank until the visible flame opened up at the rear surface of the cylinder. (See Figure 3B.) The trend in the data was that flames at higher velocities (12 and 13 cm/sec) were more stable in low-g than those with lower velocities. Flames at higher velocities did not shrink as far or fast when compared to those at lower velocities. In many cases the flames at lower free stream velocities eventually extinguished. The flame tips on these flames continued to shrink during low-g. (See Figure 3C.) The visible flame thickness decreased and the stand-off distance increased. The flame continued to shrink until the flame was only visible at the forward stagnation point. (See Figure 3D). Extinction was preceded in many cases by a series of flame oscillations as the flame tips propagated around the circumference of the cylinder. Extinction then occurred; the flame vanished within one video frame. The flame burned in reduced gravity for approximately 2 to 4 seconds prior to extinction.

Discussion

Although a quantitative comparison can not be made between the model and the experimental results (the model is for purely forced flow while the experiment was conducted in a mixed flow), an understanding of the flame behavior can be obtained by comparing their qualitative trends. In the experiments, the visible flame became thinner and the stand-off distance increased during reduced gravity. (See Figure 3.) This result was similar to results from the mathematical model. (See Figure 2.) In this figure the flame shrank in length as the percentage of heat conducted into the solid was increased. The experimental behavior of the flame as the free stream velocity increased also agreed qualitatively with mathematical model. As the velocity was increased experimentally from case to case the flame became stronger, as determined by the size and stability of the flame shape. The model predicted that increasing the velocity while keeping the percentage heat loss the same will increase the flame reactivity. (See Figure 1.)

The quenching extinction at the forward stagnation point observed in the experiments can also be interpreted

by the model results. (See Figures 2 and 3). In high speed flows (1 to 2 g's) during the airplane experiments, the flame was closer to the solid phase and the energy provided by the flame to the solid was large. In reduced-gravity the flame's heat feedback was reduced due to a larger flame stand-off distance. The solid phase temperature profile changed slower than the gas phase due to the different characteristic time scales of the gas and solid conduction. Thus, after the g-level was reduced in the airplane experiments, the ratio of heat conducted into the solid to that from the gas-phase suddenly increased. This resulted in flame shrinkage and led to a quenched extinction as demonstrated by the model results (Figure 2) and as observed in some of the experiments.

The flame oscillations exhibited by the experiment at extinction were not predicted by the model due to its quasi-steady nature.

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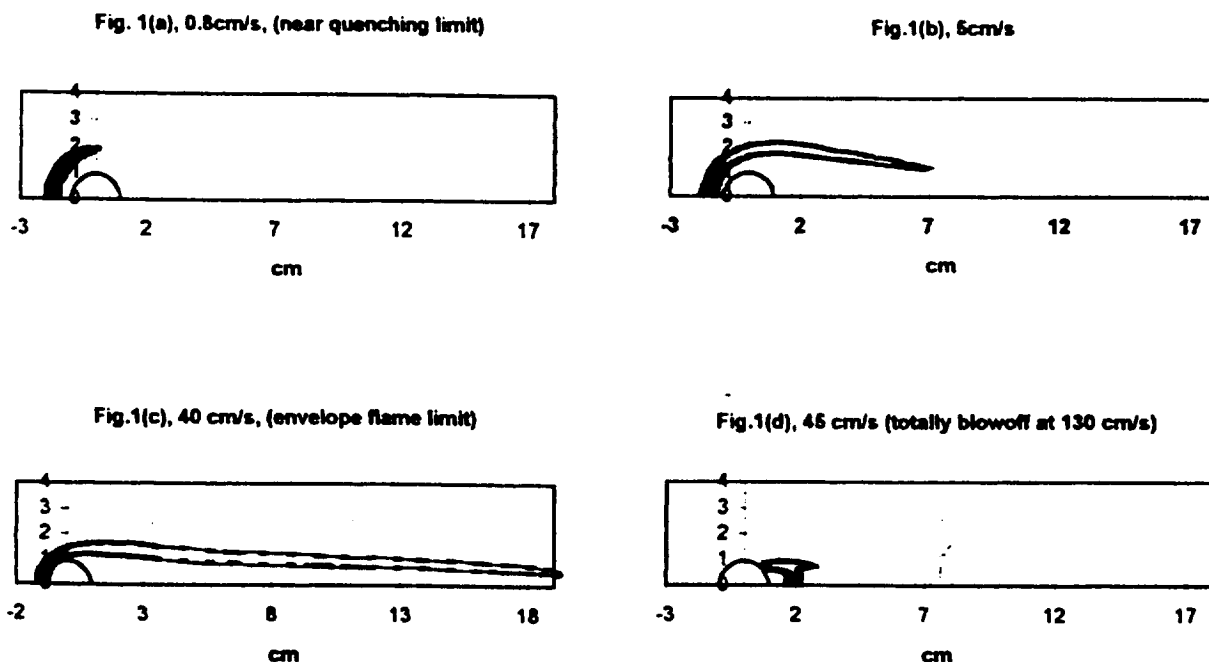


FIGURE 1. Flame Structure at Constant Heat Conduction into the Solid (30%), constant Pressure (1 atm), Constant Diameter (1.9 cm), and Variant Free Stream Velocity